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HOW SMALL IS TOO SMALL? TRUE MICROROBOTS AND NANOROBOTS

FOR MILITARY APPLICATIONS IN 2035

by

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Contents

Abstract

The Department of Defense (DOD) anticipates the realization of biomimetic bird and two-inch-insect sized systems within the 2015 – 2047 time frame. Although robot systems on the order of size of one millimeter or smaller are not explicitly specified in current DOD and United States Air Force technology roadmaps, the technological aims toward this size can be clearly implied from official documents. This research assesses the likelihood of, and barriers to, the realization of true microrobots and nanorobots (defined as sub-millimeter sized robots of micrometer and nanometer proportions, respectively) that can perform in military applications by 2035. The findings of this research are that the realization of true microrobots for military applications by 2035 is unlikely except for a single case of microrobots. Furthermore, the realization of true nanorobots for military applications by 2035 is even more unlikely. Technological advancements accrued through striving towards the goals of true micro- and nanorobots are critical towards the U.S. achieving a technological edge in more realizable-sized miniature robots for military application. Additionally, these technological advancements are critical for reducing the size and payload of a host of other military systems including satellites, aircraft, weapons, C4ISR, and portable sensors. Thus, regardless of the feasibility of sub-millimeter sized robots by 2035, the U.S. should still sponsor research and development of both true microrobots and nanorobots today.

1. Introduction

23 JAN 2035, 0032Z – An imperceptible speck pierces the thick air and enters the adversary's war room located somewhere on the other side of the planet. In his dimly lit control room in the high desert of Nevada, Capt Bright cringes slightly as he pilots his lead system across the war room. "It's still unnerving to me," he remarks to his pal at the next terminal, "I'm two freakin' feet in front of the defense minister's face and he can't even see me!" Bright perches his microrobot onto the defense minister's left epaulet, and repositions until the adversary's entire campaign plan is full view. Imagery and audio data stream in for the J-2.

After two weeks of assessing the situation, adversary analysts finally determine that all of the command and control computers in the bunker malfunctioned from the same cause some time between 0300 and 0320. It appears that the VCC pins on each microprocessor chip were severed. It was as if small explosions occurred at each pin location.

The preceding fiction may soon be fact.

1.1 Problem Background and Significance

Current trends in Department of Defense (DOD) research, development, and acquisition of unmanned systems point towards an evolution in remotely piloted or autonomous vehicles to systems the size of insects or much smaller.[1] Both DOD and United States Air Force (USAF) technology roadmaps anticipate demonstration and operation of bird and insect-sized systems capable of persistent intelligence, surveillance, and reconnaissance (ISR) and limited kinetic attack abilities by roughly the 2015 – 2047 time frame.[2] Specifically, the Air Force Research Laboratory goals are to demonstrate bird-sized systems by 2015 and insect-sized systems by 2030.[3] The Army Research Laboratory (ARL) goals are to demonstrate robust palm-sized air and ground-based systems by roughly 2018.[4]

Presently, the DOD uses the term "micro" when referring to small autonomous systems on the order of size of one to two feet in length, or bird-sized.[5,6] The DOD uses the term "nano"

when referring to small autonomous systems on the order of size of a large insect (i.e., two inches).[7] However, these systems should more appropriately be labeled "miniature" systems or robots. This research report deals with the concepts of "true" microrobot and nanorobot use for military applications; "true" meaning that the robots are of micrometer and nanometer proportions, respectively.

Henceforth, in this research report, a microrobot is defined as a robot with length on the order of 1×10^{-6} meters (one micrometer, one micron, or 1 µm) or a robot constructed from components of micron proportions. Therefore, a microrobot could range in size from 1 µm to a few millimeters (mm) in length. However, for the purposes of this research report, future microrobot projections will be limited in length to no greater than 1 mm. For size perspective, the diameter of a human hair is approximately 100 µm, and the diameter of a human red blood cell is 7 µm. From the perspective of a macro-world observer, a land, aerial, or aquatic based microrobot would appear at its largest as an ant, gnat, or plankton, respectively, and at its smallest, appear invisible. A nanorobot is defined as a robot with length on the order of 1×10^{-9} meters (1 nanometer or 1 nm) or a robot constructed from components of nanometer proportions. Therefore, a nanorobot could range in size from 1 nm to a few microns in length. For size perspective, the spacing between crystalline silicon atoms is 0.543 nm, and molecules are of nanometer size. From the perspective of a macro-world observer, a nanorobot would appear invisible.

Although systems on the order of size of one millimeter or smaller are not explicitly specified in current DOD and USAF technology roadmaps, the technological aims toward this size are clearly implied. Additionally, even though this research will focus on true microrobots of less than one millimeter in size, some of the results of this research can be extended to the

larger insect-sized microrobots because they will have to overcome some of the same technology barriers in order to be realized.

The main goal of this research is to analyze and assess the likelihood that true microrobots and nanorobots that can perform in military applications will be developed by 2035. This research will also identify key technological barriers to the development of true microrobots and nanorobots for use in military applications by 2035. Additionally, an argument will be made that the Department of Defense (DOD) should still sponsor research and development (R&D) of both microrobots and nanorobots even if their realization by 2035 is unlikely. This sponsorship is a critical catalyst for driving both the miniaturization and integration of sensors, communication systems, propulsion systems, munitions, control systems, power supplies, and packaging for use in realizing larger insect-sized systems and other military systems.

1.2 Research Paper Overview

The analysis in this paper will utilize various futures methodologies to forecast a plausible future for true microrobots, construct the plausible required system architectures for the plausible future, and argue the likelihood for that plausible future by 2035. First, background on the current state of miniature DOD robots, microrobots, nanorobots will be presented from government and technical literature in Section 2. In Section 3, a concept of operations (CONOPS) for both micro- and nanorobots will be proposed based on my own thoughts and insights gained from proposed microrobot CONOPS from the DOD or other sources. The CONOPS will be in the form of a four-quadrant futures scenario. The CONOPS will facilitate backcasting, and be used to define required robot technologies and potential environmental challenges required by the CONOPS. In Section 4, a relevance tree for the robots envisioned in

the CONOPS will be constructed. The relevance tree will deconstruct the microrobot into its required technologies and components. In Section 5, environmental scanning of DOD and public technical literature, combined with extrapolation, will be used to assess the availability of the required technologies and components, and identify technical barriers to realization by 2035. Finally, Section 6 will summarize and draw conclusions about the feasibility of micro- and nanorobots by 2035 and recommendations for the DOD's involvement with relevant funding for R&D.

2. Miniature Robot, Microrobot, and Nanorobot Background

2.1 Current DOD Miniature Robots

Table 2-1 provides a summary of current DOD miniature robot characteristics. The USAF currently employs the Battlefield Air Targeting Micro Air Vehicle (BATMAV) also known as Wasp III. The BATMAV is a flying robot and is used for situational awareness and reconnaissance in special operations.[8] The U.S. Marines and U.S. Navy also utilize the Wasp III.[9] There are several hundred such vehicles currently in the DOD inventory.

The U.S. Army currently employs the Tactical Mini-Unmanned Air Vehicle (TACMAV) which is roughly similar to the BATMAV.[10] The U.S. Army and U.S. Marines currently employ the "Toughbot," and are developing the "Throwbot ."[11] These robots are wheeled ground robots, and are used for clearing buildings and short-range reconnaissance. Fifty-one Toughbots are already fielded.

Table 2-1: Summary of current DOD miniature robot system characteristics.

System	Domain	Control	Propulsion	Payload	Size & Weight	Endurance
BATMAV (Wasp III)	air, 50-500 ft operating altitude, 10K ft max altitude	autonomous or remote	fixed wing, propeller, battery powered	GPS/INS navigation, autopilot, 2 high-resolution video cameras (front/side look), IR, L-band (1-2 GHz) data link	12×16 in, 1 lb	40 mph, 45 minutes
TACMAV	same as above w/ 11K ft max altitude	same as previous	same as previous	same as previous except no IR	20×21 in, 1 lb	50 mph, 25 minutes
Toughbot	ground	remote	wheeled, battery powered	2 video cameras, audio sensor	6×8 in, 2.1 lbs	2 hours
Throwbot	ground	remote	same as previous	1 video camera	6×2.5 in, 12 oz	2 hours

In the 2015 – 2047 time-frame, the DOD anticipates the demonstration of biomimetic miniature robots. Biomimetic implies the mimicking of movement and appearance of biological organisms such as birds or insects with flapping wings or crawling ground creatures. The goal of biomimetic operation is to enable more covert operations by allowing the robot to better blend into the expected natural environment as a bird, spider, scorpion, or flying insect.

The realization of the novel size scale of the miniature robots has been enabled by advances in micro-scale technologies mostly from the fields of microelectronics, microelectromechanical systems (MEMS), and materials science over the past 30 years. Additionally, insect-sized miniature robots suitable for military application should be achievable in the near foreseeable future.

2.2 Current Microrobots

Credible scientific research in microrobot and microrobot enabling technology has been conducted since the late 1980s[12] (including early 1990s Defense Advanced Research Project Agency (DARPA) sponsored research[13]). To date, crude microbots and microrobot components

intended for crawling,[14] flying,[15] and swimming[16] have been demonstrated for potential use in

close quarters inspection, medical, and micro/nano-nanometer manipulation/assembly

applications.[17,18] Most microrobot systems today range in size from one centimeter to a few

millimeters in length, demonstrate only crude movement under pristine laboratory conditions,

and lack any integrated electronic control circuitry, onboard power supplies, sensors, or

communication systems. Figure 2-1 shows scanning electron micrograph and captured video

images of a microrobot fabricated on a 4.5 mm square by 0.5 mm thick silicon chip.[19] The

microrobot demonstrated linear motion at 453 µm/min using 96 polycrystalline silicon thermal

actuator legs arranged in six groups that mimicked the motion of six-legged insects. The

microrobot was externally powered through three 25 µm thick tethered gold bond-wires with an

electric power consumption of 0.9 W. Figure 2-2 shows a captured video image of a 15 mm long

microrobot fabricated out of a silicon chip.[20] This microrobot demonstrated linear motion of

several mm/min using 8 silicon heated polymide joint actuator legs. The microrobot was

externally powered through three 25 µm thick tethered gold bond-wires with an electric power

consumption of 1.3 W.

(a) Under belly showing arrays of thermal actuator legs
(b) Close view of one thermal actuator leg
(c) Microrobot standing erect with a small insect atop its back
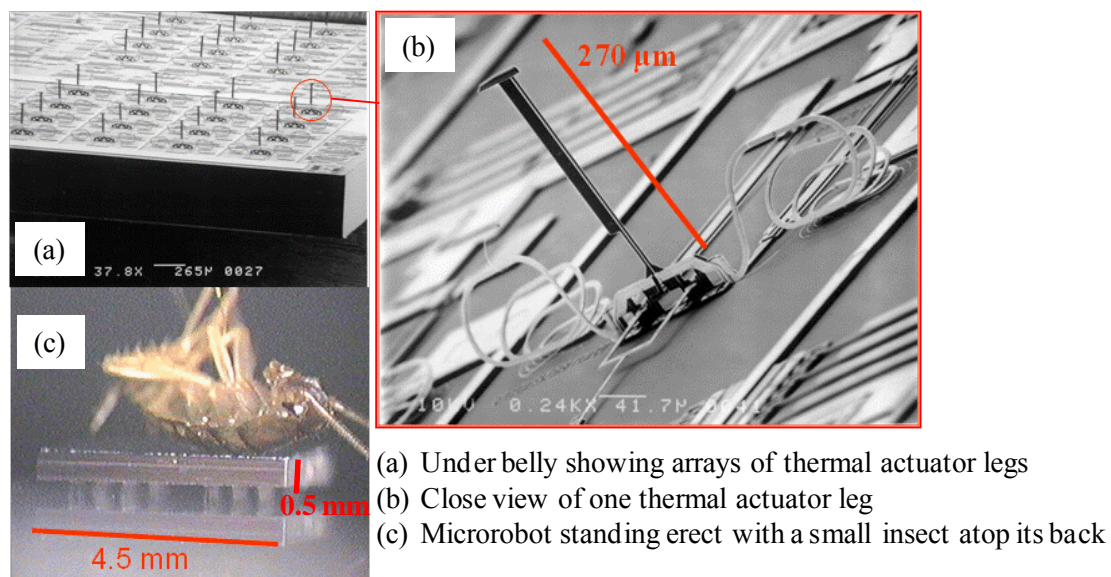
Figure 2-1: Scanning electron micrographs and video image of a 4.5×4.5×0.5 mm microrobot.[21]

(a) Standing erect under load   (b) Size and direction of motion
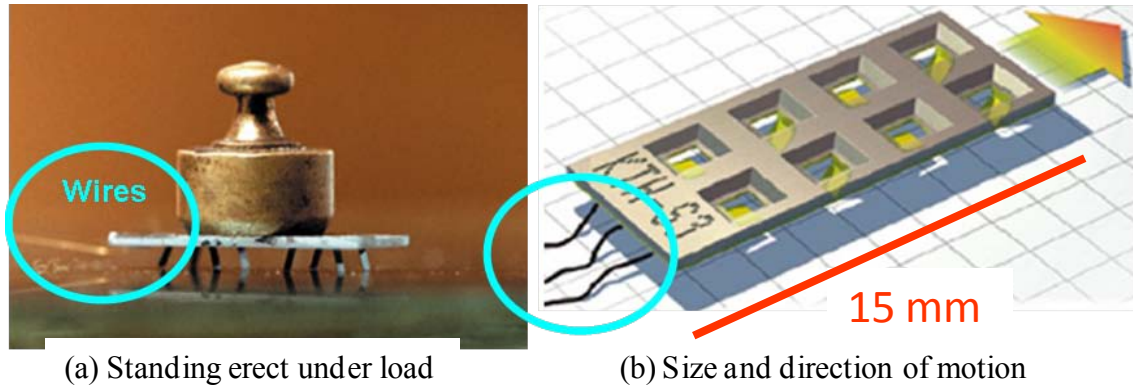
Figure 2-2: Captured video image and graphical depiction of a 15 mm long microrobot.[22]

A more integrated microrobot is that of Hollar et al., consisting of an integrated actuator foot, control circuitry, and solar cell, and was able to demonstrate crude uncontrolled linear movement on the order of a few microns/minute with an electrical power consumption of 2.6 µW.[23] This microrobot is 8.6 mm in length. Figure 2-3 shows a captured video image of this integrated and autonomous microrobot.

(a) Microelectronic control circuitry
(b) Solar cell
(c) Silicon electrostatic comb-drive motor chip
(d) Close view of electrostatic comb-drive motor
(e) Crawling foot mechanism
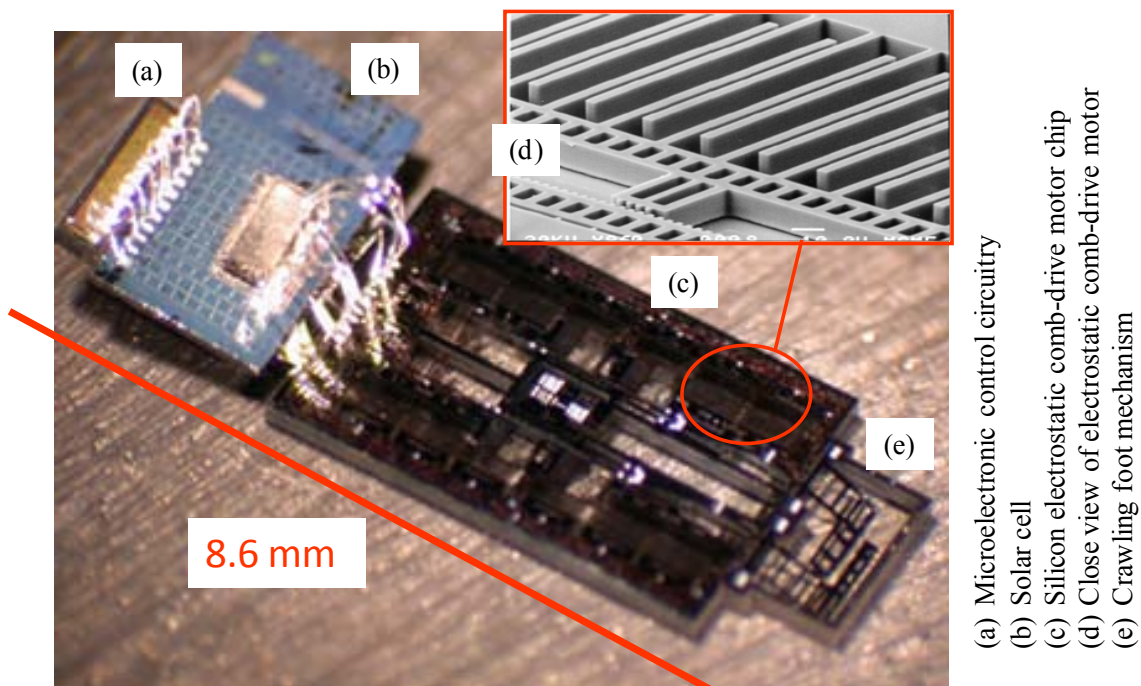
Figure 2-3: Captured video image of an integrated and autonomous microrobot.[24]

The most advanced integrated and autonomous microrobot to date is the I-Swarm microrobot.[25] The I-Swarm microrobot is approximately 4 mm by 4 mm by 3 mm tall. The I-Swarm microrobot consists of integrated solar cells used for power, light tracking, and reprogramming communication; an IR unit used for sensing and communicating with other I-Swarm microrobots; an application specific integrated circuit (ASIC) used for overall control; three piezoelectric legs used for forward, reverse, and z-axis rotation movements; a piezoelectric touch sensor; and power storage capacitors. The I-Swarm components are integrated through a flexible printed circuit board. The I-Swarm locomotion is limited to operation on a flat sheet of 8.27×11.69 inch paper illuminated by a high intensity lamp and an overhead image projection system used for programming the microrobots and displaying graphical navigation cues for the microrobots to follow.

1) Solar cells
2) IR module
3) ASIC
4) Storing capacitors
5) Locomotion unit
6) Vibrating contact sensor
7) Flexible printed circuit board
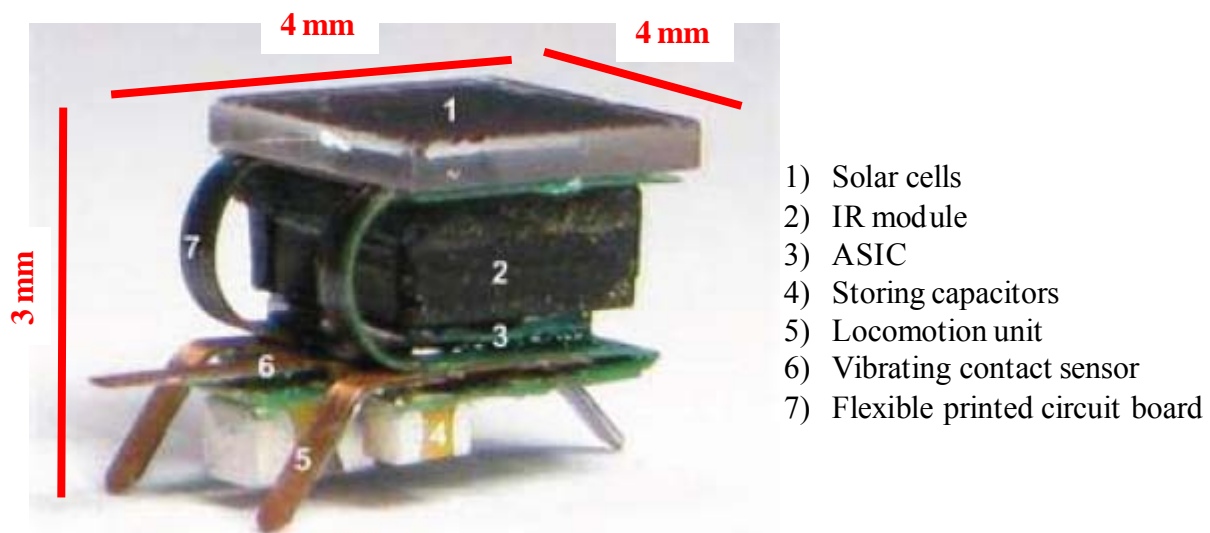
Figure 2-4: Captured video image of an I-Swarm microrobot.[26]

In summary, since the inception of microrobot research 30 years ago, enabled by the new engineering field of MEMS, the state-of-the-art of microrobots is limited to sizes greater than 1

mm in length and limited sensing and crawling operation in highly controlled laboratory environments. No integrated flying microrobots, at the scales discussed in this section, have been demonstrated yet. The micron scale of microrobot components has roughly remained the same since their inception 30 years ago. What has advanced is the growing body of knowledge of microrobot construction and motion schemes, novel integration techniques, and microelectronics capabilities. It may be another 30 years of revolutionary breakthroughs in order to reach sub-millimeter sized microrobots with robust autonomy, sensing abilities, and propulsion systems in real-world operational environments.

2.3 Nanorobots

Nanorobotics is an emerging research area, and can be generally divided into two areas: nanometer scale manipulation of nanometer sized objects and construction of nanometer scale robots.[27] The first area, nanometer scale manipulation, is already showing tangible results such as the manipulation of nanometer sized particles using an atomic force microscope (AFM) tip or the manipulation of individual atoms using the electron beam of a scanning tunneling microscope (STM).[28]

The second area, nanometer scale robots, is only theoretical. Presently, the primary goal for nanorobots is that of an assembler, a self-replicating machine used to assemble materials or objects from the "bottom-up."[29] Most research in this area focuses on computer aided modeling of biological components such as DNA or proteins in hopes of someday harnessing their natural functions in order to perform nano-scale tasks. For example, Hirabayashi et al. proposes using synthetically programmed DNA strands in order to realize various specific self-assembled DNA

structures that can perform specific tasks at the nanometer scale, such as communicating with bacteria.[30]

Nanorobots that have practical military application, like those proposed by Drexler as "universal assemblers" with the ability to re-order atoms "with the precision of programmed machines," have not yet been demonstrated in any respect.[31] The most likely contribution in the foreseeable future of the larger field of nanotechnology will most likely be in the realization of nano-scale components (i.e., sensors, control circuitry, power sources) used to help realize sub-millimeter scale microrobots.

3. Future Concept of Operations (CONOPS)

At present there exists no coherent work outlining CONOPs for microrobots' or nanorobots' use in military applications.[32] One notable contribution to microrobot CONOPS comes from a 1995 Chief of Staff of the Air Force-directed study of future capabilities required to ensure air and space dominance.[33] The study was performed by Air University through the Air Force Institute of Technology. Excerpts from the study follow.

> "Attack microbots" describes a class of highly miniaturized (one millimeter scale) electromechanical systems capable of being deployed en masse and performing individual or collective target attack. Various deployment approaches are possible, including dispersal as an aerosol, transportation by a larger platform, and full flying/crawling autonomy. Attack is accomplished by a variety of robotic effectors, electromagnetic measures, or energetic materials. Some "sensor microbot" capabilities are required for target acquisition and analysis. "Swarm" of 1mm scale flight-capable MEM(S) platforms provide unobtrusive, pervasive intervention into adversary environments and systems. Extremely small size provides high penetration capabilities and natural stealth.[34]

> "Sensor microbots" describes a class of highly miniaturized (millimeter-sized) electromechanical air and ground systems capable of being deployed en masse to collect data, perform individual and collective data fusion, and communicate that data for further processing and distribution. Various deployment approaches are possible, including dispersal as an aerosol, transportation by a larger platform, and full-flying/crawling

autonomy. Data collection is accomplished through miniaturized onboard sensors, typically restricted to one or two sensors per unit due to size and power limitations. Communications are possible by transmission through relay stations "relaybots" or physical collection of the microbots. Some applications of sensor microbots are: security net to guard own assets, surveillance and reconnaissance, and intelligence gathering on adversary assets.[35]

Overall, the CONOPS presented in this section follow directly from a military interpretation of the aforementioned commercial microrobot applications of close quarters inspection, medical, manipulation, and assembly discussed in Section 2. Additionally, concepts for microrobot CONOPS can be derived from miniature robot roles defined in the DOD "Unmanned Systems Integration Roadmap" and the "USAF Unmanned Aircraft Systems Flight Plan." These defined miniature robot roles are battlefield situational awareness, indoor or outdoor reconnaissance, surveillance, target recognition, sensing, lethal attack, irregular warfare, cyber attack, and swarming.[36,37] In essence, military microrobots will require capabilities like those of today's Global Hawks and Predators. The overall CONOPS will be presented in terms of a surface or land-based mission scenario. Microrobot and nanorobot operation in space and underwater domains are assumed to be impractical for this future scenario. Larger robots are assumed to be more suitable for space and underwater domains, e.g., space mines, directed energy offensive satellites, submarine remoras, etc.

Appendix A outlines two novel sets of four futures scenarios CONOPS for microrobots and nanorobots, respectively, as shown in Figure 3-1. The detailed future CONOPS provided in Appendix A was omitted from this section for brevity, but should be reviewed in order to fully appreciate Section 4. With reference to Figure 3-1, "Independent" implies each individual robot contains all the component functions necessary to conduct a mission alone, whereas "Distributed" implies different component functions will be distributed amongst several robots in

order to conduct a mission. "Remotely Piloted" implies that the robot will be remotely controlled during the entire mission, whereas "Autonomous" implies the robot will perform autonomously, with possible limited remote control direction, throughout the mission. Each quadrant will dictate plausible robot technology requirements.
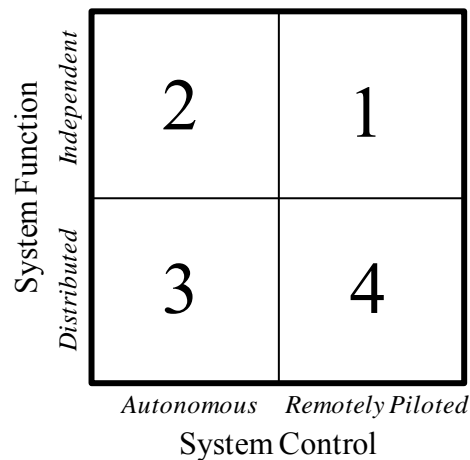
Figure 3-1: Four-quadrant futures scenario CONOPS for microrobots and nanorobots.

4. Microrobot System Components

In this section, a relevance tree for the microrobots envisioned in the proceeding section's CONOPS will be constructed. The relevance tree will deconstruct the microrobot into its required technologies and components. Following the relevance tree, each required technology and component will be discussed in detail. The section will conclude with comments on the required technologies for nanorobots.

4.1 Microrobot Relevance Tree

Figure 4-1 is an illustration of a relevance tree for the microrobots discussed in the CONOPS. For the purposes of establishing a maximum size limit baseline for the required microrobot components, several assumptions are made in this paper about the size and number of components required to construct a microrobot suitable for military applications. First, a

fabricated microrobot will probably not have a cube shape; however, for size estimation purposes this section assumes a cubic microrobot of 1 mm by 1 mm by 1 mm. Therefore, the total volume of a microrobot is assumed to be 1 mm^3. Table 4-1 represents a tabular version of the relevance tree for each quadrant microrobot, and includes allocated component quantities and volumes. Table 4-1 lists the required microrobot components or subsystems in the first column. The purpose of each component or subsystem is described in detail in Appendix B. The component and subsystem descriptions provided in Appendix B were omitted from this section for brevity, but should be reviewed in order to fully appreciate Section 5.
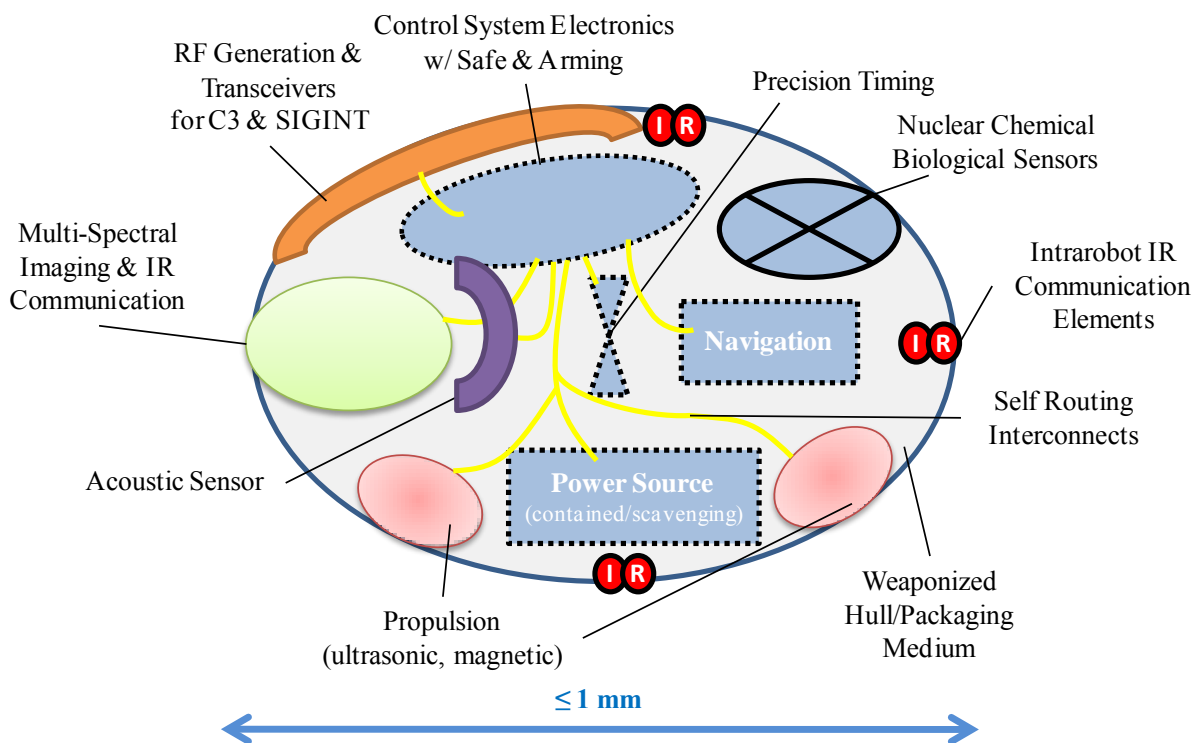
Figure 4-1: Graphical illustration of a microrobot relevance tree.

Table 4-1: Tabular microrobot relevance tree including allocated component volumes.

Component	Quadrant 1 (Ind/RP)			Quadrant 2 (Ind/Aut)			Quadrant 3 (Dis/Aut)			Quadrant 4 (Dis/RP)		
	Qty.	*Add. CE*	Vol. (mm^3)	Qty.	*Add. CE*	Vol. (mm^3)	Qty.	*Add. CE*	Vol. (mm^3)	Qty.	*Add. CE*	Vol. (mm^3)
Control Electronics*	5.35		0.259	5.35		0.259	4.9		0.258	4.9		0.258
Nuclear Sensor Elements	0.3	*0.15*	0.015	0.3	*0.15*	0.015	0.3	*0.15*	0.016	0.3	*0.15*	0.016
Biological Sensor Elements	0.3	*0.15*	0.015	0.3	*0.15*	0.015	-	-	-	-	-	-
Chemical Sensor Elements	0.3	*0.15*	0.015	0.3	*0.15*	0.015	-	-	-	-	-	-
Optical TRX Systems	2	*1*	0.097	2	*1*	0.097	2	*1*	0.105	2	*1*	0.105
Acoustic Sensor	0.3	*0.15*	0.015	0.3	*0.15*	0.015	-	-	-	-	-	-
RF TRX Elements	1	*1*	0.048	1	*1*	0.048	1	*1*	0.053	1	*1*	0.053
Timing Elements	1	*0.25*	0.048	1	*0.25*	0.048	1	*0.25*	0.053	1	*0.25*	0.053
Navigation System	1	*1*	0.048	1	*1*	0.048	1	*1*	0.053	1	*1*	0.053
Propulsion Elements	4	*0.25*	0.193	4	*0.25*	0.193	4	*0.25*	0.211	4	*0.25*	0.211
Munitions†	-	*0*	-	-	*0*	-	-	*0*	-	-	*0*	-
Power Elements	1	*0.25*	0.048	1	*0.25*	0.048	1	*0.25*	0.053	1	*0.25*	0.053
Integration Overhead (20%)			0.200			0.200			0.200			0.200
Totals	16.6	*4.35*	1.000	16.6	*4.35*	1.000	15.2	*3.9*	1.000	15.2	*3.9*	1.000

Legend: Qty. (quantity), Vol. (volume), RF (radio frequency), TRX (transceiver), Ind (independent), RP (remotely piloted), Aut (autonomous), Dis (distributed), Add. CE (additional control electronics required for each component), *quantity equals 1 central control processor plus the total of the "Add. CE" column, †munitions are part of the microrobot packing material accounted for in integration overhead

For each respective quadrant capability, Table 4-1 lists the allocated quantity units (Qty.) for each component, the additional control electronics (Add. CE) required for each component, and the allocated volume (Vol.) for each component. The control electronics row reserves one control processor for a central control function plus the total of the additional control electronics column. The allocated volume for each component is calculated by dividing 1 mm^3 by the total number of allocated components in the Qty. column and then multiplying this by the allocated quantity unit for each component. In estimating the allocated volume for each component, several subjective assumptions have been made concerning the respective sizes of each component. For example, nuclear, biological, chemical, or acoustic sensor elements are allocated approximately one third (0.3) the space of a navigation system component. Additionally, all of the additional control electronics allocations are also subjective estimates.

Furthermore, the absence of allocations for biological, chemical, or acoustic sensor elements in the Quadrant 3 and 4 columns are not meant to imply that these microrobots will not have these capabilities. Since Quadrant 3 and 4 microrobots have distributed function, they will have only a single sensing capability. This single sensing capability is symbolically allocated in the "Nuclear Sensor Elements" row.

Table 4-2 represents a relevance tree for a special case of a Quadrant 3 microrobot. This special case Quadrant 3 microrobot is a passive propulsion-less robot that simply relays sensed information from wherever it is placed or lands. This special case represents a streamlined microrobot with the minimum number of components to accomplish a plausible passive mission as described in the CONOPS. This microrobot may require either an optical or RF communication system to relay sensed information (volume allocation is represented in "RF TRX Elements"), timing elements in order to synchronize data, a navigation system in order to geolocate data, and munitions as part of the integration overhead for self-destruction.

Table 4-2: Special case, passive and propulsion-less, Quadrant 3 microrobot relevance tree showing required number of components and volume allocation for each component.

Component	Qty.	*Add. CE*	Vol. (mm^3)
Control Electronics*	3.5		0.329
Sensor Elements	1	*0*	0.094
Optical TRX Systems	0	*0*	0.000
RF TRX Elements	1	*1*	0.094
Timing Elements	1	*0.25*	0.094
Navigation System	1	*1*	0.094
Propulsion Elements	0	*0*	0.000
Munitions†	-	*0*	-
Power Elements	1	*0.25*	0.094
Integration Overhead (20%)			0.200
Totals	8.5	*2.5*	1.000

Legend: Qty. (quantity), Vol. (volume), RF (radio frequency), TRX (transceiver), Add. CE (additional control electronics required for each component), *quantity equals 1 central control processor plus the total of the "Add. CE" column, †munitions are part of the microrobot packing material accounted for in integration overhead

The primary significance of Tables 4-1 and 4-2 is that the allocated component volume

values will be used later in Section 5 to estimate the maximum component sizes required to

realize 1 mm^3 microrobots by 2035. For example, a single control electronics processor unit or a

power supply will have to fit in a volume of 0.048 mm^3 for Quadrant 1 or 2 microrobots, 0.053

mm^3 for Quadrant 3 or 4 microrobots, or 0.094 mm^3 for special case Quadrant 3 microrobots, in

order to realize a microrobot of total volume 1 mm^3. Equivalently, 5.35 control electronics

processor units will have to fit in a volume of 0.259 mm^3 for Quadrant 1 or 2 microrobots. For

simplicity, the rest of the analyses in this paper will assume a maximum size limit for any single

microrobot component of one whole volume unit. These maximum component volume units are

summarized in Table 4-3.

Table 4-3: Maximum microrobot component volumes.

	Maximum Component Volume (mm^3)	Cube Length max volume$^{1/3}$ (mm)
Quadrant 1 & 2	0.048	0.363
Quadrant 3 & 4	0.053	0.376
Quadrant 3 Special Case	0.094	0.455

4.2 Nanorobot System Description

The nanorobot will be constructed from synthesized or naturally occurring molecular

biological components. The nanorobots will require the capability to replicate or move in or

along the object they are placed as they process their target material. The nanorobots will

require the capability to either physically or chemically rearrange the molecules or atoms of the

target material. The nanorobots will neither communicate nor collect data. They will simply

react with their target material until their process has culminated or their reaction has become limited.

5. Analysis and Evaluation

In this section, environmental scanning of DOD and public technical literature, combined with extrapolation, will be used to assess the availability of the required microrobot and nanorobot technologies and components by 2035. Additionally, this section will identify technical barriers to, and plausible solutions for, realization by 2035.

5.1 Microrobot Component State of the Art Evaluation, Availability Extrapolation, and Suggestions for Overcoming Technical Barriers

5.1.1 Control Electronics

State of the art microprocessor electronic circuits are currently fabricated on crystalline silicon chips approximately 1 cm by 1 cm by 0.5 mm thick – "thumb-nail in size." The primary factor that determines the required size of electronic circuits and support systems, given a fixed transistor size and technology, is processing speed. Processing speed can be increased either by increasing the clock speed or by using parallel processing. Increasing the clock speed allows faster processing speed on a single chip or circuit, but requires more electrical power (e.g., 143 Watts for a high performance processing unit with a heat sink) which in turn is dissipated in the form of heat. The heat is usually removed by a system of heat-sinks and forced convection fans. However, the heat removal system can consume considerably more space than the microelectronic circuitry. Parallel processing is achieved by using redundant microelectronic

circuits that break the processing down into several parallel tasks. In this manner, a microelectronic circuit can process information quickly, even with a slower clock speed, because the processing task is being performed in parallel. The drawback in terms of size for this method is the requirement for more chip surface area for the additional parallel processing circuitry.

Lower power consuming microelectronic circuits are realized by decreasing the clock speed and reducing the power supply voltage. The reduction of power supply voltage is driven by several factors: reduction of transistor power consumption, reduced transistor channel length, and reliability of gate dielectrics. Current portable low-cost, hand-held, and uncooled battery operated circuits currently consume approximately 3 Watts per 1 cm^2 chip.

Figure 5-1 is a plot of projected electronics chip size. The curve in Figure 5-1 extrapolates that in 2035, a 0.486 mm by 0.486 mm electronics chip will hold the same number of transistors, with overhead, as a 1 cm^2 chip does today. This should indeed be plausible since the 2035 chip size corresponds to a transistor (including overhead) density of 233,582 million transistors per cm^2 whereas the atomic surface density of crystalline silicon is 678,313,306 million atoms per cm^2. Based on the microrobot maximum component volumes listed in Table 4-3, this chip will meet the Quadrant 1 & 2 volume restrictions as long as the substrate thickness is no greater than 0.048 $mm^3 \div$ (0.486 mm $\times$ 0.486 mm) = 0.203 mm. Figure 5-2 shows the extrapolated power requirement for the 2035 chip of 0.007 Watts (W) or 7 mW. This power requirement will be used later in this section to estimate required microrobot power supply capacity.
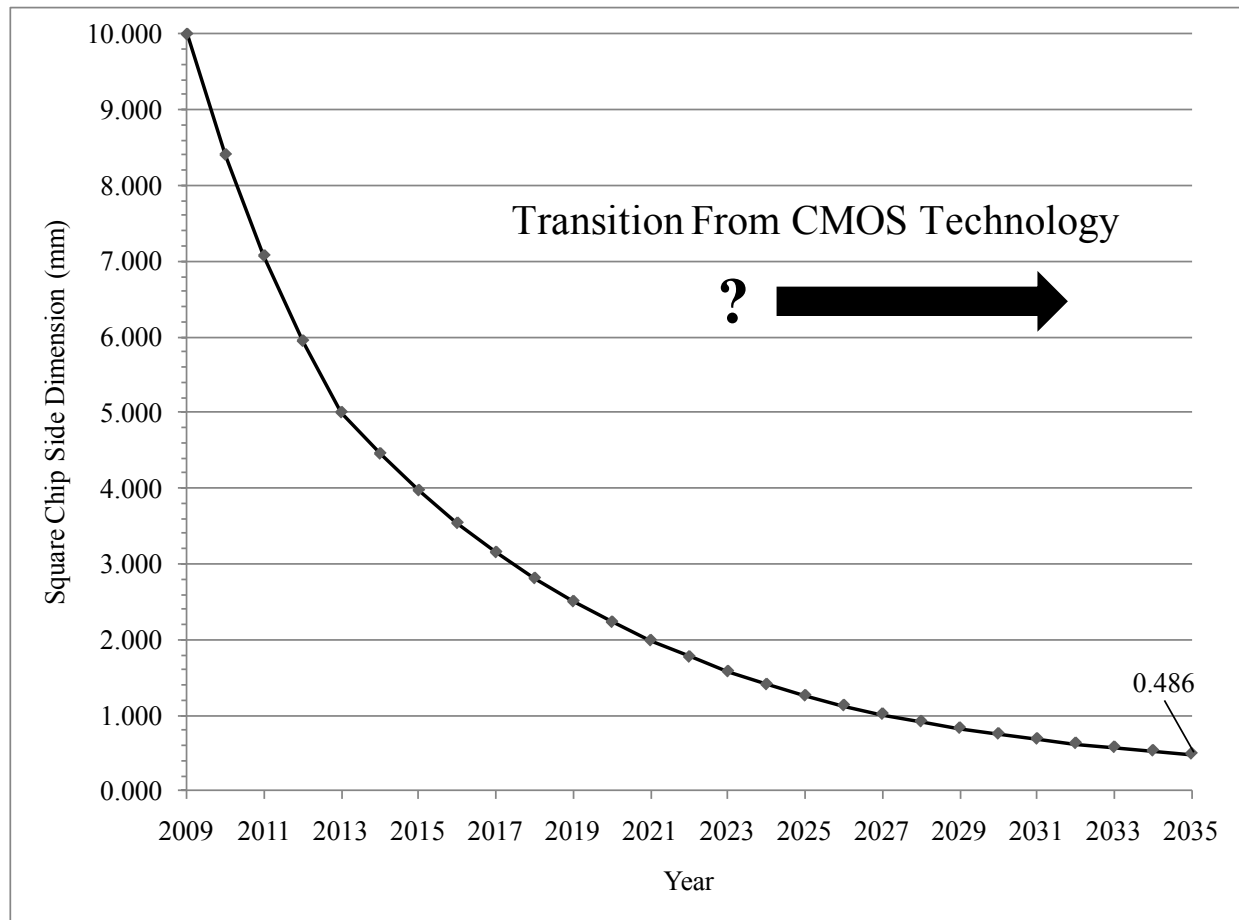
Figure 5-1: Plot of projected high-volume microprocessor chip size. This plot was constructed from data from the 2009 International Technology Roadmap for Semiconductors (ITRS) predicted number of transistors (including the logic core, memory, and interconnection overhead) per approximately 1 cm^2 high-volume microprocessor chip for the period 2009 to 2024.[38] Data from 2025 to 2035 was extrapolated by curve fitting a 4th order polynomial to the 2009 through 2024 data and extrapolating to 2035. The curve extrapolates that in 2035, a 0.486 mm by 0.486 mm electronics chip will hold the same number of transistors, with overhead, as a 1 cm^2 chip does today.
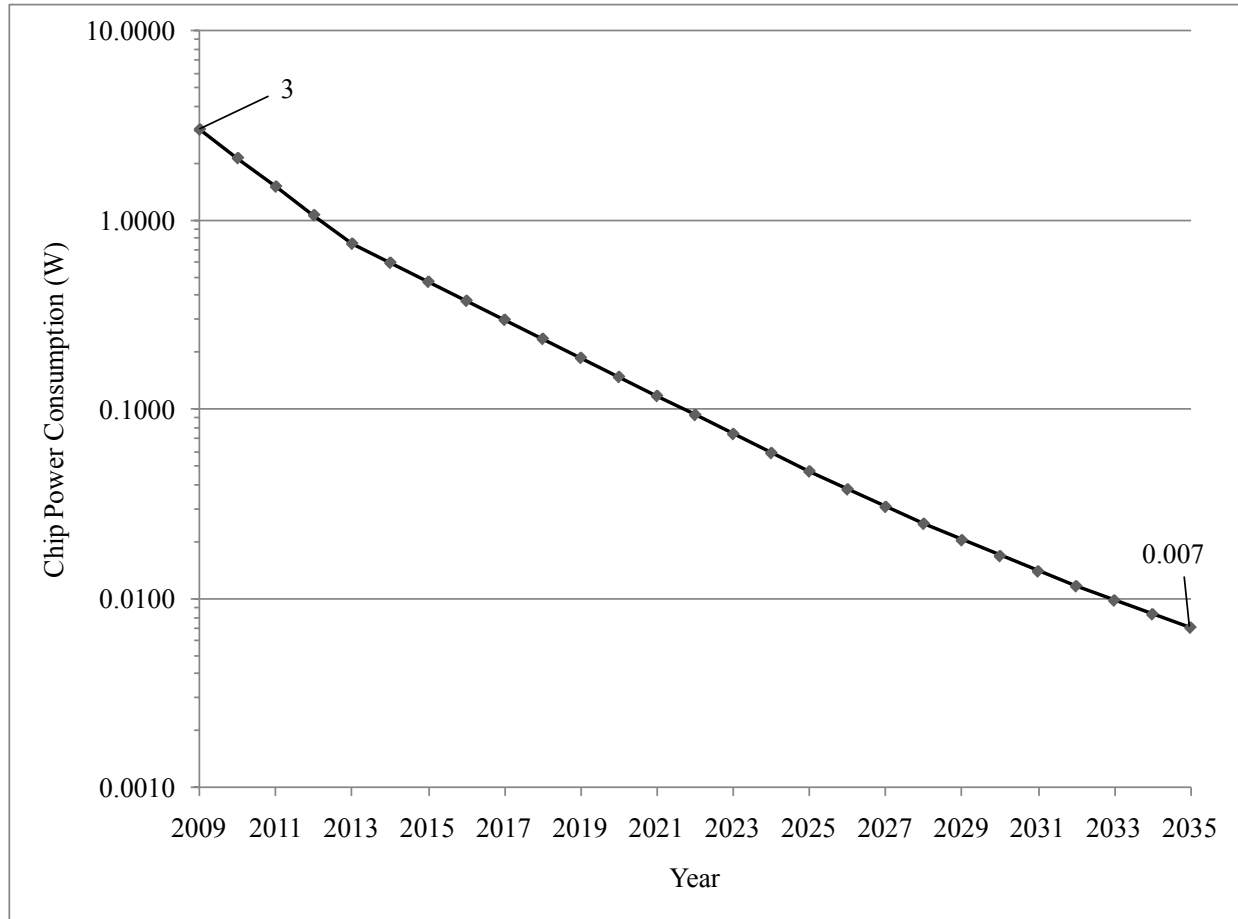
Figure 5-2: Plot of high-volume microprocessor chip power requirements corresponding to the decreasing chip sizes in Figure 5-1. The curve shows the extrapolated power requirement for the 2035 chip of 0.007 Watts (W) or 7 mW. This plot was constructed from the data in Figure 5-1 and assumes a target power consumption of 3 Watts, per low power 1 cm^2 chip, is held as a design constant from 2009 to 2035.[39]

At some point, transistor technology will have to transit away from the current

complementary metal oxide semiconductor (CMOS) technology in order to reach the target chip

size by 2024 and, consequently, by 2035. Potential replacement technologies include carbon-

based nano-electronics, spin-based devices, ferromagnetic logic, atomic switches, and

nanoelectromechanical (NEMS) switches. Additionally, although the projected microprocessor

size is on track to meet a single microrobot maximum component volume, the multiple

microprocessor chips required to run a complete microrobot will have to be stacked together in

some fashion in order to fit inside a microrobot. This will require a three-dimensional (3-D)

integration technique that is currently not realized.

In summary, current commercial electronics trends are on track to yield electronics

suitable for incorporation into microrobots by 2035. However, the DOD may have to drive the

transition from CMOS technology to keep pace with the current trend should the commercial

sector choose not to. Additionally, the DOD may have to drive R&D in reliable 3-D circuit

stacking integration. This agrees with the National Research Council (NRC) Committee on

Implications of Emerging Micro- and Nanotechnologies assessment that next generation

electronic devices such as scaled CMOS, Single-electron transistors, spin-based electronics,

molecular electronics, and carbon nanotube electronics may be available for application some

time within the next 10 – 40 years.[40]

5.1.2 Nuclear, Biological, and Chemical Sensors

Current commercial nuclear, biological, and chemical sensors are field effect transistor or

diode junction based.[41] Additionally, NEMS sensors based on resonating thin films and

nanowires[42] and optical based nanoparticle systems[43] are currently being developed. The

individual sensor element sizes, especially for transistor based sensors, are already well under the

microrobot maximum component volumes listed in Table 4-3. Presently, these sensors are

normally fabricated on relatively large substrates too large for microrobots. The only technical

challenge for the future is in integrating these sensors on smaller substrates that will meet the

microrobot maximum component volumes. This should be achievable by 2035. This agrees

with the NRC's assessment that MEMS- or nanotechnology-based chemical and biological

sensors may be available for application some time within the next 10 years.[44]

5.1.3 Multispectral Optical Components and Transceiver Elements

Current charge coupled display (CCD) 640x480 pixel (0.5 Megapixel) chips are approximately 2 mm by 2 mm by 0.5 mm thick. Complete digital micro-camera systems including optical components, at present, are rarely smaller than 5 mm by 5 mm by 5 mm.[45] Decreasing the size of imaging systems may require new paradigms such as compound eye systems found in small biological organisms. Compound eye systems could be realized through the use of microlenses and microlens arrays currently under development.[46] Additionally, the complete imaging system can be further miniaturized using other MEMS based optical components with advanced packaging techniques also currently under development.[47]

Microrobots of the future may require high resolution imaging to accomplish their mission versus the low resolution systems discussed above. One way to realize higher resolution for microrobot imaging systems is to decrease the imaging pixel size. State of the art imaging pixel sizes can range in size from 10 µm by 10 µm to 4 µm by 4 µm.[48] However, reducing the size of imaging pixels and associated optical components may run into physical barriers due to the diffraction of light since the visible light wavelengths range from 0.38 to 0.72 µm and IR wavelengths of interest can range up to several hundred micrometers. If the microrobots were to operate in a distributed sense in order to achieve higher resolution imaging, where each robot represents a few pixels, the current inexistence of suitable miniaturized high precision position and timing subsystems for composite image correlation and construction presents a technology barrier to microrobot distributed imaging.

Adding the requirements of night vision, IR imaging, and transceivers for line-of-sight intra-microrobot communications further complicates the situation. Night vision would require

miniaturized light amplification components. High performance IR imaging would require miniaturized pixel cooling subsystems unless a suitable miniaturized uncooled IR imaging system is realized by 2035. Optical components for millimeter sized intra-microrobot communications have recently been developed. The I-SWARM microrobot uses a spatially arranged surface-emitting light emitting diode and photo detector line-of-sight microrobot intra-communication subsystem that measures 3 mm by 3 mm by 1 mm thick.[49]

In summary, current state of the art imaging systems do not meet microrobot maximum component volumes. However, R&D is pointed in the right direction. Current commercial trends are driving the miniaturization of imaging systems for hand-held devices and medical instruments. Furthermore, since imaging technology is closely related to standard integrated circuit technology, it may follow standard integrated circuit miniaturization trends to 2035. However, the DOD may have to drive R&D in order to reach sub-millimeter sized high resolution imaging systems, night vision components, and uncooled IR imaging systems. Furthermore, the DOD may have to drive R&D of non-CCD/CMOS based imaging pixels for both visual and uncooled IR imaging.

5.1.4 Acoustic Sensors

An example of a state of the art micro-sized acoustic sensor is fabricated from piezoelectric thin films and measures 600 μm by 600 μm by 2.2 μm thick with a total volume of 0.0008 mm^3.[50] Since the size of this device is much less than microrobot maximum component volume requirements (0.048 mm^3), this device should be on track to complement microrobot systems by 2035. Reduction in thin film width dimensions (under 600 μm), in order to be able to physically incorporate this into a microrobot while still remaining sensitive to the 20 Hz – 20

kHz audio range, could pose a technical challenge. However, this challenge can most likely be overcome by reducing the thickness of the sensing film appropriately. The primary technical challenge for the future is in integrating this sensor on substrates or with microelectronics that will meet the microrobot maximum component volumes. This should also be achievable by 2035. This agrees with the NRC's assessment that MEMS- or nanotechnology based multispectral sensors may be available for application some time within the next 10 years.[51]

5.1.5 Multispectral RF Components and Transceiver Elements

One of the more challenging areas of miniaturization is with RF systems. Communication for remote control or intelligence and reconnaissance data telemetry via current RF system paradigms may be impractical due to physical barriers at this small scale regarding antenna efficiency, monolithic microwave integrated circuit (MMIC) size, and lack of transmission power to reach the outside world. For example, for efficient transmission, a dipole antenna should span a quarter of the respective RF communication wavelength. Assuming a quarter wavelength antenna of 1 mm would require a RF communication frequency of 75 GHz which is in the US Industry Standard W-band, International Standard EHF-band, or Military Standard M-band.[52] Development of W-band MMIC components and design techniques is currently underway. In terms of power requirements, assuming 0 dBi gain microrobot transmit and receive antennas, 75 GHz, and a very good receive sensitivity of -120 dBm (very slow data transmission rate), microrobots could theoretically communicate at a distance of 2500 ft with 7 mW of available transmission power (same power estimated for a single integrated circuit processor chip in 2035), 1000 ft with 1 mW, and and 30 ft with 1 μW.[53] Alternatively, assuming a higher data transmission rate with a receiver sensitivity of -80 dBm, microrobots could

theoretically communicate at a distance of 30 ft with 7 mW, 10 ft with 1 mW, and 4 inches with

1 µW of available transmission power. Current state of the art broadband SIGINT systems

including RF processing, amplifier, and filter components are on the order of one meter in size.

It is highly unlikely that such a system can be reduced in size to meet microrobot maximum

component volumes by 2035.

In summary, it is unlikely, given size and power constraints, that robust RF

communication and sensing systems will be available by 2035 for practical microrobots without

major technological breakthroughs. This roughly agrees with the NRC's assessment that certain

MEMS-based RF sensor components may be available for application some time within the next

10 – 40 years.[54] Furthermore, it is unclear whether or not MMIC technology will follow

standard integrated circuit miniaturization trends in order to meet microrobot component size

constraints by 2035. One recent discovery using carbon nanotube resonators holds promise.[55]

Using nano-resonators, a whole new paradigm in RF system design may enable further

miniaturization; however, adequate transmission power in order to communicate with the outside

world may still be an issue, since this seems to be independent of RF system technology.

Finally, another recent discovery that may be used to overcome size and transmission power

barriers is communication using quantum entanglement.[56]

5.1.6 Precision Timing

Miniaturization of rubidium and cesium-based atomic clocks is currently an aggressive

area of research.[57] Miniaturized atomic clock systems are on the order of 1 cm in size and

consume approximately 75 - 360 mW of power.[58,59] The current R&D paradigm consists of the

direct miniaturization of large-scale atomic clocks based on the absorptive properties of rubidium

and cesium vapor. The greatest technical challenge in atomic clock miniaturization is the

miniaturization and packaging of the absorption cell also known as the physics package. It is

unclear whether atomic clocks based on this paradigm can be further miniaturized in order to

meet microrobot maximum component volumes by 2035. The DOD should drive R&D into

further miniaturizing atomic clocks by two orders of magnitude more, or find alternative

paradigms in precision time keeping.

5.1.7 Navigation Components

Another of the more challenging areas of miniaturization is with navigation systems.

Current miniaturized INSs are based on MEMS inertial elements including accelerometers and

gyroscopes. The inertial elements will have to be of suitable grade to accomplish the mission.

Inertial element grades are classified into three categories of increasing performance: tactical

grade, navigation grade, and military grade. With few exceptions, most MEMS inertial

components are tactical grade at best. However, tactical grade components may be suitable for

the microrobot mission. For example, some of today's miniature military aerial systems and

munitions take advantage of the Honeywell HG1930 MEMS inertial measurement unit, which is

roughly 2 inches in diameter, 1.3 inches in height, and consumes less than 3 W of power.[60]

MEMS accelerometers and gyroscopes are electrostatically actuated resonating masses usually

fabricated from silicon and are on the order of size of a few hundred micrometers in width and a

few micrometers in thickness. Although each device is relatively small in size, the combination

of three accelerometers, three gyroscopes, reference devices, control electronics, and other

supporting components required to realize true navigation can become sizeable. Inertial element

performance is a function of the mass of the element. The smaller the inertial element, the less

sensitive it becomes. Therefore, there is a physical barrier to the further decrease in size of these elements.

In summary, R&D is pointed in the right direction in trying to miniaturize navigation systems. However, given the physical inertial barrier combined with the current size of MEMS based navigation systems, it is unlikely that navigation systems based on the current MEMS paradigm can be further miniaturized in order to meet microrobot maximum component volumes by 2035. The DOD should drive R&D into further miniaturizing navigation systems based on alternative paradigms.

5.1.8 Propulsion

Another challenging area of miniaturization is microrobot propulsion. Even if all the aforementioned microrobot internal component technical barriers could be overcome by 2035, nature itself presents a significant exterior obstacle. The state of the art in microrobot propulsion was previously covered in Section 2 and was based on crawling. At this size scale, the microrobot will have to surmount several unintuitive obstacles in order to traverse distances. Crawling along surfaces will be impractical for several reasons, including the fractal lengthening of a surface's topology at the sub-millimeter scale, which could result in a never-ending journey through canyon-like crevices and around mazes of boulder-like particulates. Crawling microrobots could be knocked off center by particulates, or become entrapped in a quagmire of dust. A flying propulsion system will have to be powerful enough to enable the microrobot to penetrate breezes, strong air currents, dust, and rain. The propulsion system will also have to be powerful enough to break the microrobot free from the surface tension of moist surfaces, small films of liquids, and the attraction of charged surfaces or environmental particulates. The

propulsion system will have to reach relatively high velocities in order for the microrobot to travel to the target in a timely manner and achieve enough momentum to penetrate the aforementioned environmental conditions.

The DOD projects that the miniature insect-sized "Nano-Flapping Air Reconnaissance Vehicle" will achieve technology readiness level (TRL)-6 by FY13 with a less than 2 inch wingspan and a maximum weight of 10 grams.[61] Theoretically, a 1 mm wingspan can provide enough lift to propel true microrobots.[62,63] However, it still remains to be demonstrated whether actual microflight can be achieved in practice, or whether it will be an effective form of propulsion for microrobots employed in a military mission. Most likely, a currently unknown method of propulsion may have to be discovered in order for true microrobots to surpass nature for military applications. One possible wingless method of flight propulsion may be found in acoustic streaming jets.[64] Additionally, due to the extremely small masses at the microscale, microscale objects effectively operate in microgravity conditions similar to operation in space. Therefore, another possible method of microflight propulsion could be one that takes advantage of the earth's magnetic field.[65]

In summary, 30 years have transpired since the inception of the microrobot and microrobot propulsion components. To date, only crude crawling and swimming of millimeter-scale robots in highly controlled laboratory environments has been demonstrated. Based on this trend, it may be another 30 years before robust microflight is realized. This agrees with the NRC's assessment that MEMS-based propulsion may be available for application some time within the next 10 – 40 years.[66]

5.1.9 Micromunitions

In order for microrobots to deliver appreciable kinetic affects to a target, new explosive materials must be found that pack a bigger punch into a smaller package. A possible material candidate currently under investigation includes nanoporous silicon that is reported to have more than double the energy output of TNT.[67] Other examples include metastable intermolecular composites, sol-gels, and functionalized carbon nanotubes.[68] It is unknown whether materials like these will provide enough energy for microrobot mission accomplishment. Another possible munition could be a micro-sized nuclear weapon.

In summary and to this author's knowledge, there is no current dedicated investigation into realizing microscopic explosive charges for application with microrobots. Further research should be conducted in order to further define microrobot target sets, associated required kinetic effects, and suitable energetic materials. It is unknown whether or not an effective explosive-laden microrobot is a feasible concept or will be available by 2035.

5.1.10 Power Supplies

Arguably, the most challenging area of miniaturization is in the ability to provide a long endurance power supply for autonomous microrobots. Microrobots have been demonstrated to be powered or actuated using tethered wires, close proximity inductive coupling of large coils, close proximity capacitive coupling, vibration tables, thin film batteries, close coupled magnetic fields, pulsed laser beams, or solar power – all impractical for microrobot long distance autonomous operations.[69] Potential microrobot power supply schemes can be divided into two categories: self contained or environment scavenging.

Examples of self contained power supplies currently under development include fuel cells, turbine powered electrostatic generation, and thin film batteries which are all still too large or unable to provide enough sustainable energy for microrobots. One promising technology for self-contained long-term power generation is alpha and beta source radioactive decay, or nuclear batteries.[70] Another technology is a hybrid micro-scale MEMS fuel cell thin film lithium (Li) ion source.[71] In order to appreciate the current inadequacy of self contained power supplies for microrobots, an example is in order. Consider a Quadrant 1 or 2 microrobot that must provide power to the following major subsystems: control electronics, optical, RF, timing, navigation, and propulsion, altogether representing 14.35 components requiring power (see Table 4-1). Next, assume each of the 14.35 components requires the same power as a single microprocessor chip of 7 mW, for a total 14.35×7 mW ≈ 100 mW required power. Now assume the microrobot was powered by a thin film Li ion battery that fits into the maximum microrobot component volume size of 0.048 mm^3 from Table 4-3. Assuming a thin film Li ion energy density of 200 Whr/kg and a Li compound density of 8×10^{-7} kg/mm^3, the battery can provide 200 Whr/kg $\times$ 8×10^{-7} kg/mm^3 $\times$ 0.048 mm^3 = 7.68×10^{-6} Whr of power. Therefore, the battery would be able to power the microrobot while all systems are functioning for 7.68×10^{-6} Whr / 0.1 W = 7.68×10^{-5} hours (0.3 seconds).

Examples of environment scavenging power supplies currently under development include electromagnetic inductive coupling, electrostatic capacitive coupling, piezoelectric vibration, thermoelectric, pulsed laser, and photovoltaic.[72] Another example was demonstrated with silicone elastomer polydimethylsiloxane cantilever legs with rat cardiomyocyte heart-cells cultured on their surfaces.[73] These microrobot legs demonstrated movement for up to two weeks while immersed in physiological liquids. All of these power source methods could provide a

source of indefinite power as long as they can be scaled down to fit within a microrobot and the microrobot can remain in the presence of the respective external stimuli or condition. Remaining within the external stimuli would prove impractical based on the microrobot CONOPS defined in this research.

In summary, R&D is pointed in the right direction in its search for long endurance miniaturized power supplies. The DOD projects that "opportunistic power grazing" technology for larger robot systems will achieve TRL-6 by 2031.[74] However, no suitable power supply for robust autonomous microrobots exists at present. Unless a significant technological breakthrough occurs between now and 2035, suitable power supplies for microrobots are unlikely by 2035. This agrees with the NRC's assessment that MEMS-based power sources may be available for application some time within the next 10 – 40 years.[75]

5.1.11 Integration: Assembly, Interconnection, and Packaging

In order realize complete and robust microrobot systems in the future, they will have to be suitably mass assembled from all of the aforementioned subsystems. One-by-one manual machine-assisted assembly will be impractical due to the large quantities of microrobots required. During microrobot fabrication, all microrobot components will have to be assembled into their proper relative positions, electrically or optically interconnected with each other, and suitably sealed together (packaged) in order to protect the internal components from environmental contamination, while at the same time provide suitable external interfaces for the optical transceivers, biological sensors, chemical sensors, acoustic sensors, and propulsion elements.

Most likely, due to their small size, microrobots will not be assembled using current machine-automated mass manufacturing paradigms. One feasible mass manufacturing technique could be to fabricate thousands of copies of complete microrobot systems on a single substrate, deposit and pattern a final protective thin-film coating over each robot, and then subdivide the substrate into individual robots. Currently, however, the aforementioned microrobot subsystems are fabricated using disparate technologies and materials. This condition will most likely persist into the foreseeable future. Therefore, any plausible manufacturing technique must accommodate the assembly of individual subsystems fabricated from disparate technologies. Research and development has been poised for this inevitability, as evidenced in the investigation of micro and nano self-assembly techniques, which include the self arrangement or positioning of micro-scale components by harnessing the surface tension of liquids, forces of magnetic and electric fields, adhesion of functionalized surfaces, strategically positioned micro-actuators, vibration, fluid flow forces, centrifugal forces, shrinkage of polymers, and geometric matching.[76,77]

Assuming machine-automated micromanipulation technology will not be able to assemble complex 3-D arrangements and make intra-subsystem electrical connections required by the microrobots postulated in this research, the following self-assembly paradigm is proposed. In this paradigm, it is assumed that the microrobot packaging medium will be engineered to facilitate three functions: assembly, interconnection, and weaponization. First, each individual microrobot component must incorporate the following additional design features: 1) chemically functionalized edges and/or surfaces, 2) an assembly facilitating geometry, 3) a packaging-medium-phobic surface for those component surfaces that must face the exterior of the microrobot, and 4) self-routing electrical interconnection pads. Next, all required components

for an individual microrobot will be injected into a droplet of the packaging medium. Once in the packaging medium droplet, the components will orient themselves with respect to each other via the attractive forces of the functionalized edges and surfaces, the repulsive forces of the packaging-medium-phobic surfaces, and their assembly facilitating geometries. Next, upon an external stimuli, the self-routing interconnection pads will form electrical pathways to their matching interconnect pads amongst the other components. The formation of the electrical pathways is facilitated by the packaging medium chemistry and is analogous to the growth of a biological nervous system. Ultimately, the packaging medium will cure, providing a hard encasing for the microrobot. The assembled microrobot will also be spheroidal in shape due to the surface tension of the liquid packaging medium before curing. The packaging medium will also serve as the explosive material for self destruction or the delivery of kinetic effects. In the case that self-routing interconnects are not feasible, the self-routing interconnection pads could be replaced by tuned optical communication transceivers. In this case, the packaging medium must be engineered to provide total internal optical reflection so that the tuned optical transceivers on one component can communicate with their matched sets on other components regardless of location. Additionally in this case, interconnections with the power supply must somehow be hard connected.

In summary, current micro assembly techniques are not able to assemble, interconnect, and package microrobots as postulated in this research. It is unknown if this ability will be realized by 2035. The NRC's assessment is that some suitable assembly and packaging technologies may be available for application some time within the next 10 – 40 years.[78]

5.2 Nanorobot Feasibility Evaluation

With respect to nanorobots, the same technical challenges that will plague microrobots will be magnified by several orders of magnitude. Additionally, due to physics at this scale, remote communication and information storage may be impossible.[79] Nanorobots will have to be employed in an exclusively autonomous manner. Even if nanorobots are realizable, they will not be able to process their target material because the energy required to break and make atomic bonds will render atomic rearrangement unfeasible.[80] Furthermore, even if the atomic rearrangement function is realized, the time required for nanoscale objects to complete the macroscale sabotaging transformation of enemy materials would be impractical.[81] For these and a host of other practical physical limitations, the realization of nanorobots as postulated in this research may be unlikely regardless of time frame.

6. Summary and Conclusions

In Section 2 it was shown that the current state of miniature DOD robots is vehicles on the order of a foot in size that can fly or roll on the ground with wheels with video and audio reconnaissance capability. Additionally, the DOD goal is to realize biomimetic bird, and two-inch-insect, sized systems within the 2015 – 2047 time frame. Then the current state of complete microrobot systems was shown to be robots on the order of a half of centimeter in size with crude crawling and limited serial optical communication capability in highly controlled laboratory environments. Furthermore, it was shown that nanorobots are not close to being demonstrated. In Section 3, a plausible future military CONOPS was proposed for both micro- and nanorobots composed of four-quadrant robot system designs. In Section 4, a relevance tree was utilized to deconstruct the robots into subsystems required to accomplish the missions

envisioned in the CONOPS. In Section 5, each subsystem was analyzed and assessed to

determine availability by 2035, and technical barriers and possible solutions were listed. Table

6-1 summarizes the assessments from Section 5. Table 6-2 shows an assessment of the

availability of microrobots and nanorobots by 2035.

Table 6-1: Summary of microrobot subsystem analysis and assessment from Section 5.

Microrobot Subsystem	Current R&D Vector	R&D Driven Commercially?	DOD Focused R&D Required?	Available by 2035?	Technology Breakthrough Required?
Control Electronics	appropriate	yes	maybe	likely	yes
Nuclear Sensors	appropriate	yes	maybe	likely	no
Biological Sensors	appropriate	yes	maybe	likely	no
Chemical Sensors	appropriate	yes	maybe	likely	no
Optical Systems	appropriate	yes	yes	possible	yes
Acoustic Sensors	appropriate	yes	no	likely	no
RF Systems	appropriate	yes	yes	unlikely	yes
Precision Timing	appropriate	yes	yes	unlikely	yes
Navigation Systems	appropriate	yes	yes	unlikely	yes
Propulsion	appropriate	maybe	yes	unlikely	yes
Munitions	needs focus	no	yes	unlikely	yes
Power Supply	appropriate	yes	yes	unlikely	yes
Integration	appropriate	yes	yes	unlikely	yes

Table 6-2: Assessment of the availability of microrobots and nanorobots by 2035.

Robot System	Available by 2035?
Quadrant 1 Microrobots	unlikely
Quadrant 2 Microrobots	unlikely
Quadrant 3 Microrobots	unlikely
Quadrant 4 Microrobots	unlikely
Special Case Quadrant 3 Microrobots	possible
Nanorobots	unlikely

Based on present technical literature from around the world, cutting edge research is

currently underway in the areas of miniaturized components and technologies required to

construct true microrobots. However, key technical challenges and barriers exist in the further

miniaturization of electronics, optical systems, RF systems, precision timing, navigation systems,

propulsion, munitions, power supplies, and component integration – making realization of true

microrobots by 2035 unlikely.   Prospects for overcoming these challenges were discussed in

Section 5, including next generation electronic components, nano-resonator based RF systems and sensors, quantum entanglement communication, acoustic streaming propulsion systems, nuclear or environment scavenging power sources, self-routing nervous-system-like interconnects, and novel packaging/self-assembly mediums. One possible exception is the realization of special case Quadrant 3 microrobots, which are passive propulsion-less robots that simply relay sensed information from wherever they are placed or land. Special case Quadrant 3 microrobots are similar in concept to "smart dust" research that has been underway for the past several years.[82] The realization of nanorobots for military applications may be unlikely regardless of time frame. In fact, present-day Information Operations core capabilities such as Electronic Warfare and Computer Network Operations are more practical for accomplishing the military missions envisioned for nanorobots.[83]

If technical challenges are not overcome, larger insect-sized robots may be the only practical choice for realization by 2035. However, technological advancements accrued through striving towards the goals of true micro- and nanorobots are critical towards the U.S. achieving a technological edge in more realizable-sized miniature robots for military application. Additionally, these technological advancements are critical for reducing the size and payload of a host of other military systems including satellites, aircraft, weapons, C4ISR, and portable sensors. Thus, regardless of the feasibility of sub-millimeter sized robots by 2035, the U.S. should still sponsor research and development of both true microrobots and nanorobots today.

Appendix A: Detailed CONOPS

A.1 Ingress

A.1.1 Ingress of Quadrant 1 Robots: Independent and Remotely Piloted

Microrobots, the ultimate in stealth due to their size, will be delivered (airdropped or ground released) to the general target area by a larger host such as a manned/unmanned vehicle, a kinetic projectile, or a human host.[84] Because of their small mass, microrobots will be highly survivable during high accelerations and decelerations such as those experienced by a tank or artillery shell. For example high performance munitions such as the 105 mm and the 120 mm armor piercing fin stabilized discarding sabot (APFSDS) produce very high in-bore accelerations, on the order of 60,000 G's, where 1 G is the acceleration due to gravity. Theoretical predictions for silicon micro-scale objects suggest survivability up to 136,000 G's.[85] The ability of microrobots to traverse relatively large distances to the general target area on their own will be as plausible and practical as the ability for sub-millimeter biological organisms, such as gnats or fleas, to perform the same feat. Therefore, it is unlikely that microrobots will be able to traverse large distances to the general target area, in a timely and reliable manner, on their own. For microrobots, relatively large distances will be defined by the endurance of their propulsion system, and will be assumed in this CONOPS as any distance over a mile, with the exception of the ability to make course corrections during a high altitude air drop. Travel modes of crawling or swimming are assumed to be impractical, and are discussed in more detail in Section 5.

Once released from the host platform, an internal safe and arm mechanism will activate the microrobot. Depending on the mode of microrobot communication, the microrobots will be controlled from the host delivery platform or some other nearby control or relay platform. Under remote control, the microrobots will fly to their final targets through caves, ducts, or cracks. During ingress to the final target, some of the microrobots may be positioned in order to set up a radio frequency (RF) or optical communication relay chain in order to communication with the outside world. The establishment of a communication relay chain will be dependent on the magnitude of isolation of the final target operating area.

Several microrobots will be delivered by the host platform. Depending on the specific mission, the number of microrobots will include enough to establish a communication relay chain and enough to perform the specific mission with redundancy. Controllers will have to operate using a remote control system suitable for maintaining control of several microrobots. Quadrant 1 microrobots will require some form of cooperative artificial intelligence in order to aid in the coordinated control of several microrobots.

Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

A.1.2 Ingress of Quadrant 2 Robots: Independent and Autonomous

Ingress procedures for Quadrant 2 microrobots will be identical to Quadrant 1 microrobots with the exception that they will fly to their final targets through caves, ducts, or cracks using a combination of predefined waypoints, target coordinates, and artificial intelligence. Just as moths home in on light and mosquitoes home in on heat, the artificial intelligence of microrobots will home in on various multispectral signatures while maneuvering

around obstacles. Multispectral signatures would include electronic emissions, chemicals (i.e., biological or synthetic – e.g., DNA, scents, explosives, fuel, etc.), sounds, light, images, or heat. The artificial intelligence of Quadrant 2 microrobots will also have to handle some form of cooperative behavior in order to aid in the coordinated movement of several microrobots.

Quadrant 2 microrobots may not require a communication relay chain during ingress unless their mission requires the transmission of data to or from an isolated operating area. Therefore, fewer microrobots may be delivered by the host platform.

Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

A.1.3 Ingress of Quadrant 3 Robots: Distributed and Autonomous

Ingress procedures for Quadrant 3 microrobots will be identical to Quadrant 2 microrobots. Potentially more Quadrant 3 microrobots will be delivered by the host platform than for Quadrant 1 microrobots. Depending on the specific mission, the number of microrobots will include enough to establish a communication relay chain (if required) and enough to perform the specific mission with distributed function and with redundancy.

Nanorobots will have Quadrant 3 capability. Due to their extremely small size, each nanorobot will only posses a singular capability – therefore, they are classified as distributed in function. Similarly, because of their nature and small size they will not be remote controllable – therefore, they are also classified as autonomous in control. Quadrant 3 nanorobots will not have target homing and obstacle navigation abilities like Quadrant 2 and 3 microrobots. Nanorobots will have to be delivered precisely to their target by a larger host such as a microrobot, a larger manned/unmanned vehicle, or a human host.

A.1.4 Ingress of Quadrant 4 Robots: Distributed and Remotely Piloted

Ingress procedures for Quadrant 4 microrobots will be identical to Quadrant 1 microrobots. More Quadrant 4 microrobots will be delivered by the host platform than for Quadrant 1 microrobots. Depending on the specific mission, the number of microrobots will include enough to establish a communication relay chain and enough to perform the specific mission with distributed function with redundancy.

Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

A.2 Mission

A.2.1 Mission of Quadrant 1 Robots: Independent and Remotely Piloted

Microrobots will reach their targets such as open areas of enemy activity, command posts, offices, hideouts, computer/weaponry circuit boards, antennas, satellites, desks, light fixtures, perched atop an enemy soldier's hat or body part, etc. Microrobots will be used to gather various multispectral (electronic signals, sound, images, chemical signatures, etc.) intelligence; reconnoiter; release individual or collective explosive charges, poisons, or corrosives; reprogram equipment; or sabotage with plausible deniability. Gathered data will not be stored for later retrieval, but will be transmitted back to the control station in real or near real-time.

Microrobots will hover, reconnoiter, or fine-traverse stationary objects using their flying propulsion system. Motion such as crawling will be performed through fine hopping using their flying propulsion system.

Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

A.2.2 Mission of Quadrant 2 Robots: Independent and Autonomous

The mission of Quadrant 2 microrobots will be the same as Quadrant 1. An additional mission for Quadrant 2 microrobots may be passive monitoring. In this case a propulsion system would not be necessary. These microrobots would be delivered during egress, and passively monitor the target area from wherever they have landed.

Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

A.2.3 Mission of Quadrant 3 Robots: Distributed and Autonomous

The mission of Quadrant 3 microrobots will be the same as Quadrant 1 with the exception of distributed operation. For example, one microrobot may capture images, while another captures audio, while another gathers signals intelligence (SIGINT), while yet another delivers kinetic effects. Alternatively, the collection of a single type of information may be distributed. For example, if the video resolution of a single microrobot is not sufficient to capture meaningful images alone, several microrobots may have to work in concert to form a synchronized composite image similar in function to an insect's compound eye. Additionally,

Quadrant 3 microrobots may also perform a propulsion-less passive monitoring mission similar to Quadrant 2 microrobots.

Due to the nature of a nanorobot, the mission of Quadrant 3 nanorobots will probably be like a synthetic "virus" targeted against enemy materiel and, possibly, personnel. In essence, the mission of Quadrant 3 nanorobots will be a targeted chemical reaction. For example, nanorobots will render enemy materiel such as explosives and computer processors inert, reprogrammed, or reengineered.

A.2.4 Mission of Quadrant 4 Robots: Distributed and Remotely Piloted

The mission of Quadrant 4 microrobots will be the same as Quadrant 1 with the exception of distributed operation. Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

A.3 Egress

The egress procedures for all quadrant microrobots and nanorobots will be the same. Microrobots and nanorobots will be considered expendable and will remain at the target area at the end of the mission. Reverse engineering or exploitation of a microrobot would be difficult, but not impossible. An enemy analyst could observe the exterior construction of a microrobot using a high-powered optical microscope or scanning electron microscope. Furthermore, nondestructive inspection of the microrobot will be virtually impossible due to the packaging technique of the microrobot. However, an analyst could use a focused ion beam (FIB) to cut the microrobot, and then observe interior cross sections of the microrobot using transmission electron microscopy (TEM). Ultimately, if exploitation of a microrobot is a concern, the

microrobot can self-destruct or dissolve via dual-use reactive packaging medium. Due to the extremely small size of nanorobots, the collection and exploitation of nanorobots will be impractical.

A.4 Countermeasures

To counter microrobots and nanorobots, an adversary would have to deny their presence and ability to communicate. A detection capability would be impractical. Because of the robot's invisibility due to its small size, if an adversary were to try to monitor the electromagnetic spectrum for microrobot communication, they would not know whether the detected signals were from some distant source or a robot. Ultimately, an adversary would have to resort to some broadband low power jamming at their site as a preventative measure to deny microrobots' ability to communicate. Jamming may be undesirable to the adversary if it interferes with their own operations. Line-of-sight optical communication by microrobots would be virtually impossible to detect and deny. In order to deny the presence of microrobots on the order of 1 mm or smaller, an adversary would have to operate in a clean-room or semi-clean-room type environment that utilizes carefully sealed enclosures with air duct filtration capable of blocking particles smaller than 1 mm in diameter. At a minimum, an adversary may have to construct enclosures that meet US FED STD 209E Class 100 or ISO 4 standards that statistically block particles greater than 5 μm in diameter. Ultimately, most adversaries may deem countermeasures against microrobots logistically impractical.

A.5 Logistics and Disposal

Microrobots and nanorobots will be mass produced and constructed as single expendable items. They will be stored in mission tailored dispenser cartridges ready for loading on a host delivery platform. The robot loaded mission dispenser cartridges would be stored in the same clean and dry manner that conventional ammunition is stored in order to prevent premature fouling or corrosion. The only maintenance required would be pre-mission interrogation to confirm data links and microrobot system readiness. If an unacceptable number of microrobots failed, the dispenser cartridge would be discarded. Depending on the microrobot power source, microrobot sensor chemistry, and nanorobot composition, microrobots and nanorobots will have limited shelf-lives. Unused microrobots and nanorobots will be incinerated.

A.6 Ethics

Microrobots and nanorobots may be perceived as chemical or biological weapons by the public, especially if used against personnel, and thereby consider them to violate certain *jus in bello*. A possible reason for this perception is that, due to the small size of these robots, the public may liken them to vapors or particulates harmful to humans. However, microrobots are distinctly different from chemical or biological agents. Even though a microrobot could enter a human's body through the mouth, nose, or ears, they are no more dangerous than if a human were to swallow a bullet or a radio. Legally, microrobots should not be classified as chemical or biological agents. Nanorobots, however, will be constructed from a combination of natural or synthesized biological and chemical components. Depending on their specific mission, nanorobots may differ from chemical or biological agents by their designed function. Legally, nanorobots may be classifiable as a chemical or biological agent. A key consideration of the

legal classification of microrobots and nanorobots may hinge on whether or not they are used against personnel.

Appendix B: Detailed Description of Required Microrobot Components and Subsystems

B.1 Control Electronics

Control electronics will be used as the overall control system for the microrobots and to control the various subsystems of the microrobots. The microrobots will probably be hard-coded as non-reprogrammable state machines versus being reprogrammable. Reprogramability would require more electronic real estate in terms of memory to hold the execution instructions, and additionally would be somewhat impractical due to the tedium of having to reprogram masses of individual tiny objects. Additionally, the electronics are assumed to be low power, low voltage systems such as those found in portable low-cost, hand-held battery operated devices. High power, high performance electronics would require additional heat dissipation systems, and thereby require additional space in the microrobot. Finally, the overall control system will be responsible for functions such as safe and arming.

B.2 Nuclear, Biological, and Chemical Sensors

The nuclear, biological, or chemical (NBC) sensors will probably be among the smallest devices inside the microrobot. These sensors will be either individual multi-particle sensing elements or arrays of elements each tuned for a specific target particle. The biological or chemical sensors would require openings through, or interfaces at, the exterior of the microrobot in order to "breathe" or sense the ambient air. Nuclear sensors could be completely contained in the microrobot since the sensed ionizing radiation could penetrate the exterior of the microrobot and reach the sensor. These sensors will require some amount of control electronics in order to correct for sensor drift, condition the sensor operation, and process collected data. Alternatively,

it may be possible to cross-utilize the optical and RF transceivers to perform some type of spectroscopy to derive the presence of ionizing radiation or biological and chemical elements. This cross-utilization could potentially eliminate the need for separate NBC sensors.

B.3 Multispectral Optical Components and Transceiver Elements

The microrobots will be outfitted with regular and IR imaging capability for collecting video images. The video images are required for navigation, ISR, tracking, and obstacle avoidance. Additionally, the microrobots will require IR transmitter and receiver elements placed around the microrobots body for the purpose of communicating with other microrobots (intra-robot communication) for coordination or relaying information. This system will require optics, a significant amount of control electronics for controlling the imaging sensors and signal processing, and possibly light amplification components for night vision. The imaging capability will be among the larger microrobot components. Additionally, these sensors would require optical interfaces at the exterior of the microrobot.

B.4 Acoustic Sensors

The microrobots will be outfitted with acoustic sensors for collecting sounds such as enemy voice communication, footsteps, or gunfire. This sensor will be among the smaller devices in the microrobot, and will require some amount of control electronics for signal processing.

B.5 Multispectral RF Components and Transceiver Elements

The microrobots will be outfitted with the ability to receive and transmit RF for communication such as remote control and data telemetry. Additionally, this subsystem would be required for RF based target tracking and SIGINT. This capability will require larger microrobot components, specifically some form of antenna, amplifiers, filter elements, local oscillators, and a large amount of RF and non-RF control electronics. Ideally, this capability will require some form of security such as encryption.

B.6 Precision Timing

Precision timing element is required in order to synchronize and correlate data for fusion, image reconstruction, or communication. Since part of the microrobot's mission is to penetrate isolated locations where global positioning system (GPS) timing may be unavailable, an independent timing source would be necessary. This capability will require some amount of control electronics.

B.7 Navigation Components

A navigation system is required for general navigation and for geolocation of collected data. This component will be an inertial navigation system (INS) consisting of three accelerometer elements, three gyroscopic elements, possibly a GPS receiver, possibly magnetometers, an altimeter, and control electronics for sensor element control, conditioning, and data filtering/fusion. The GPS/INS system would be used for navigation and microrobot attitude control until the microrobot enters a GPS denied environment, at which point the navigation system would have to rely on inertial data alone.

B.8 Propulsion

The microrobots will possess a flying based propulsion system with the exception of special case Quadrant 3 microrobots. A crawling based propulsion system will be impractical for several reasons discussed in Section 5. The propulsion system will require some amount of control electronics.

B.9 Micromunitions

Micromunitions are required in order to deliver explosive or corrosive affects to the target and for self-destruction. The micromunition will not be a separate payload, but is assumed to double as the structural material of the microrobot in order to maximize overall size efficiency. Upon command from the central control electronics, the weaponized microrobot structure will explode or dissolve. It is assumed that the microrobots will have to cooperate and appropriately mass at the target in order to deliver appreciable kinetic effect.

B.10 Power Supplies

The most critical component of the microrobot is the power supply. It is required to power all the microrobot components and therefore must be able to provide enough energy over the duration of the mission to do so. The power supply may be the largest component of the robot, and will either be self contained, environment scavenging, or a combination of both. Environment scavenging means power is somehow collected from the microrobot's surroundings. Although most likely impractical for this application, a solar cell is an example of a power scavenging device.

B.11 Integration: Assembly, Interconnection, and Packaging

During microrobot fabrication, all components will have to be assembled into their proper relative positions, electrically or optically interconnected with each other, and suitably sealed together (packaged) in order to protect them from environmental contamination, while at the same time be able to provide suitable external interfaces for the optical transceivers, biological sensors, chemical sensors, acoustic sensors, and propulsion elements.

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